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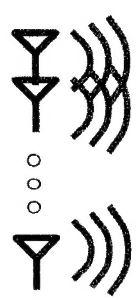
Robust MIMO Wireless Communication in the Presence of Interference Using Ad Hoc Antenna Arrays

Dr. Daniel W. Bliss
& Amanda M. Chan



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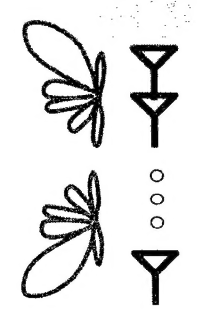

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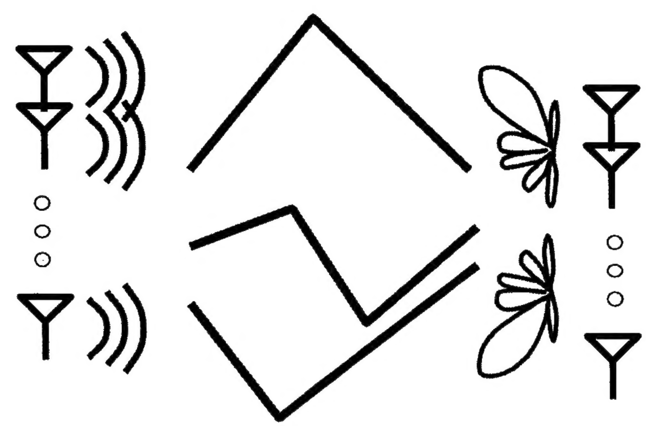
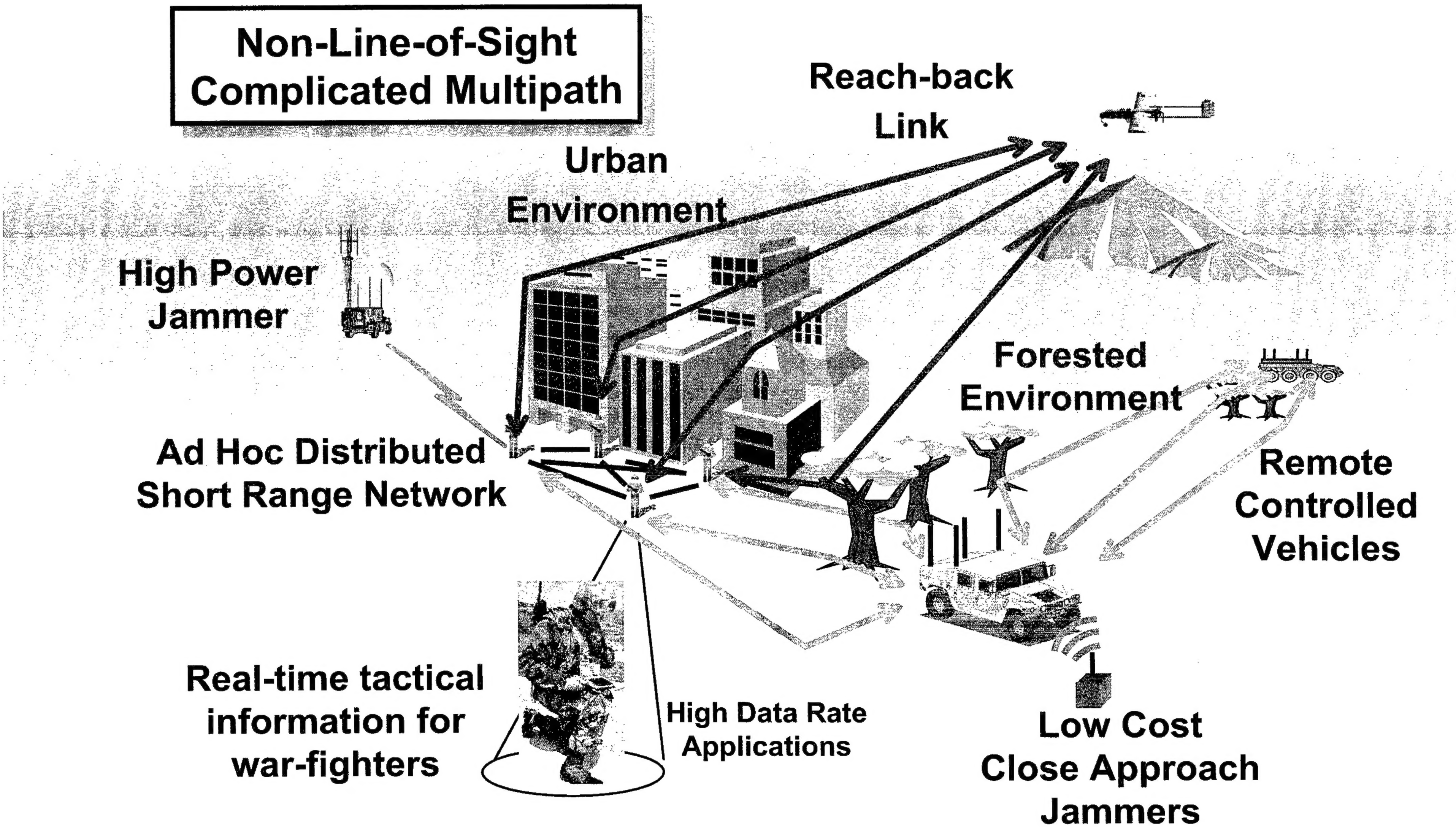
Topics
MIMO Communication

- **Introduction**
  - Military wireless communication
  - MIMO definition
  - Ad hoc antenna networks
- **MIMO Theory**
- **Phenomenology**
- **Receiver**

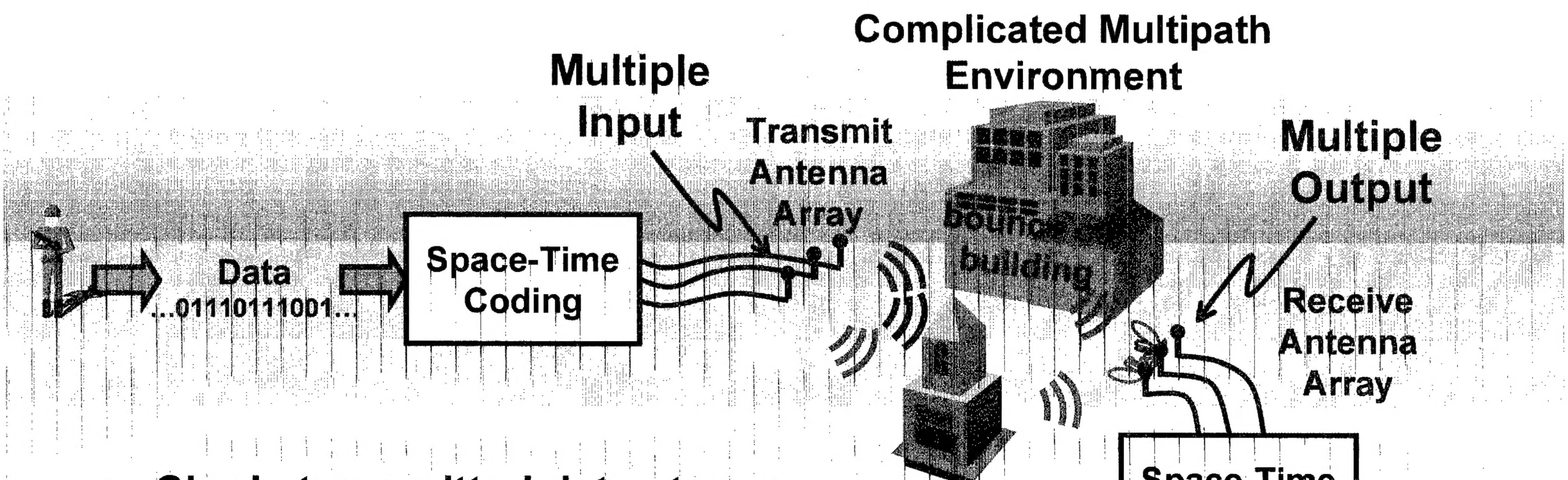


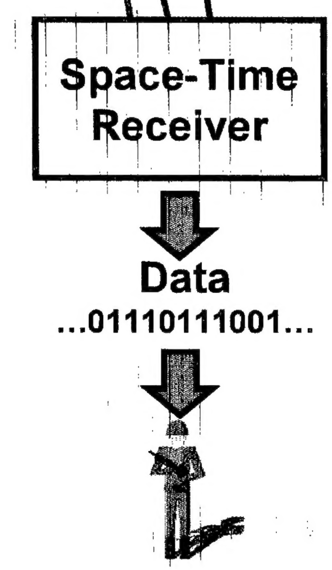
Advanced Military Wireless Communications



MIMO Communication

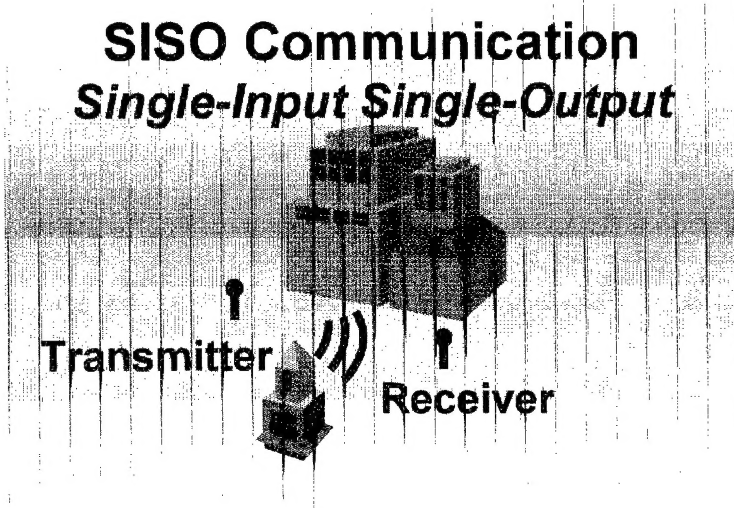
Multiple-Input Multiple-Output

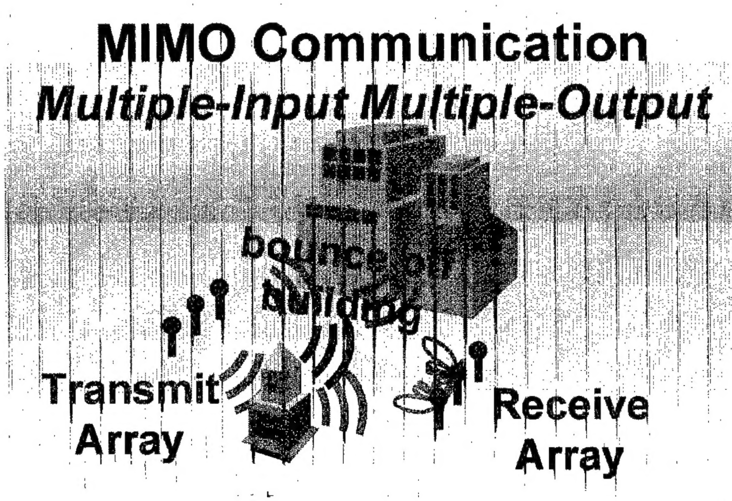




- Single transmitted data stream
- Single received data stream
- Employ array of antennas at both transmitter and receiver
- Employ multiple modes through environment
  - Not just point-to-point beamforming

Advantages of MIMO Communication

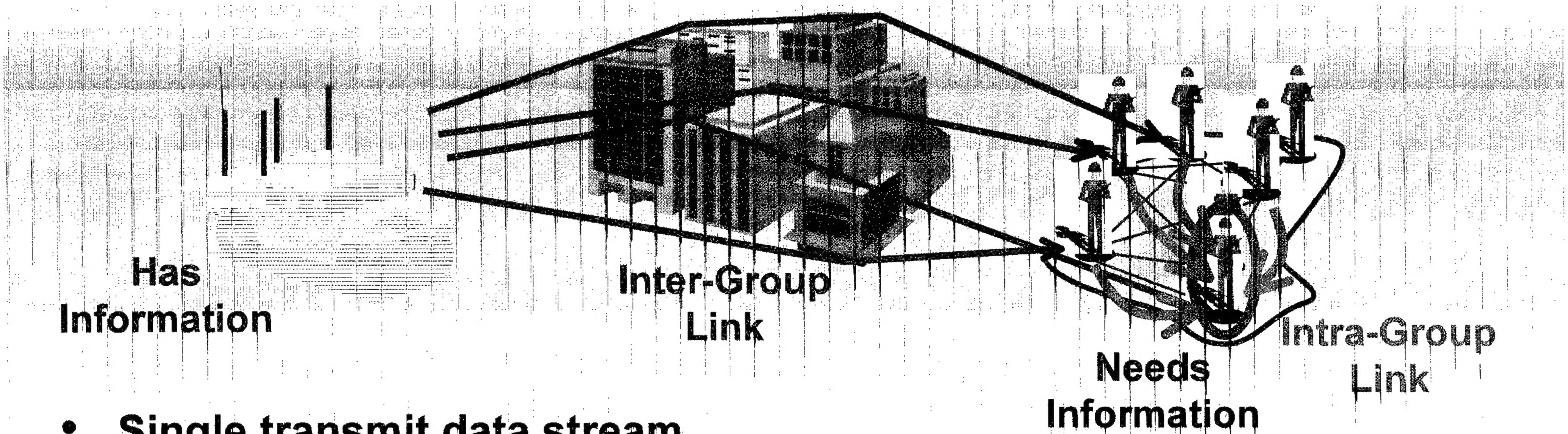




- Coherent receive beamforming
  - Gain
  - Jammer mitigation
- Transmit spatial diversity
  - Fading mitigation
  - Shadowing mitigation
  - Jammer avoidance
- Enables high spectral efficiency
  - Enables high data rates given limited bandwidths
  - Low duty cycle communication

Distributed Ad Hoc Antenna Arrays

Multiple-Input Multiple-Output

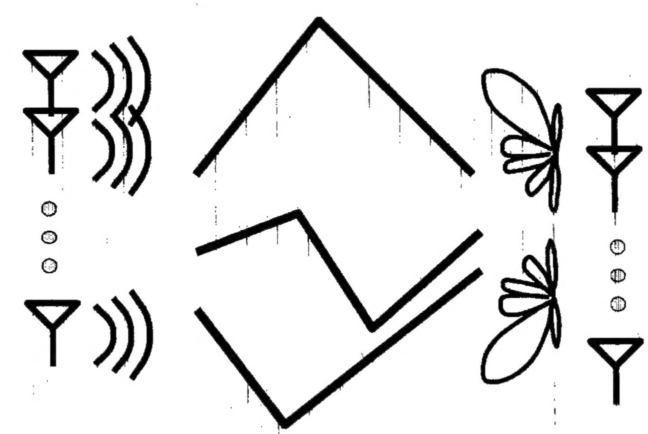


- Single transmit data stream
- Single received data stream
- Employ users as antenna array
  - Coherently process received signal
- Use local network to move distributed data to/from interested user

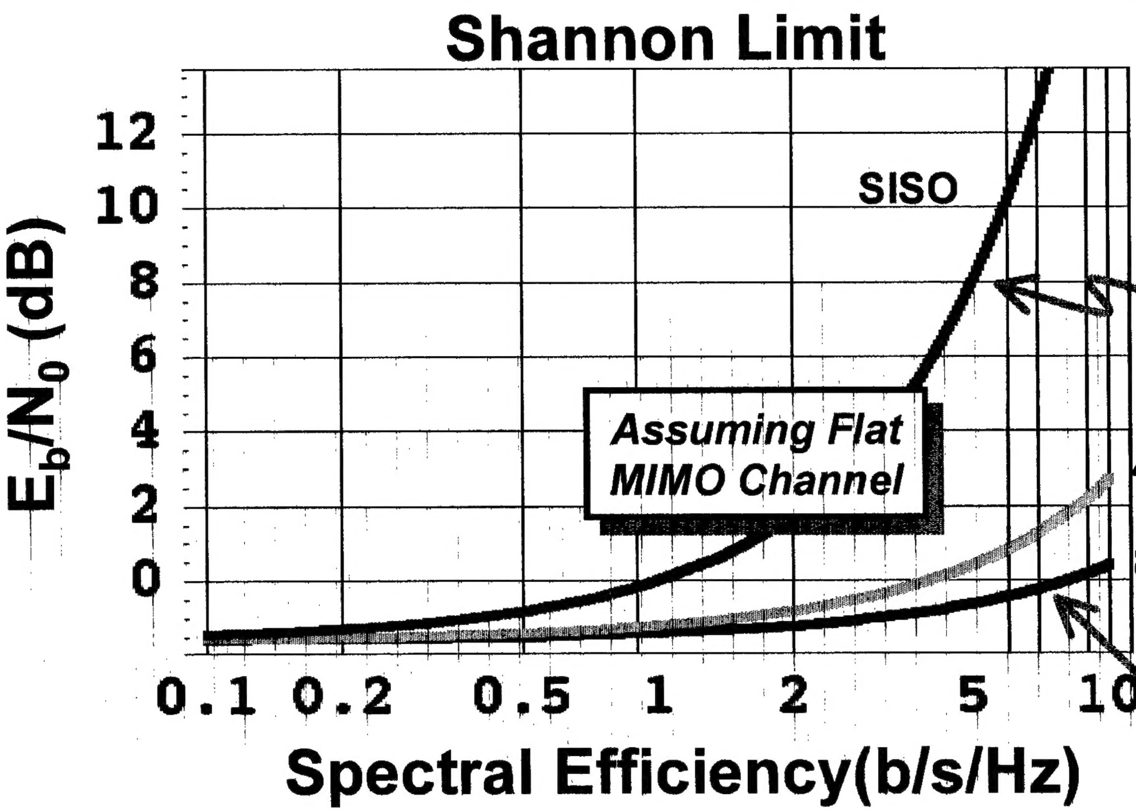
Issues
- Local networking
- Relative local oscillator errors

Topics
MIMO Communication

- Introduction
- **MIMO Theory**
  - Capacity
  - Phenomenology
  - Interference Mitigation
  - Space-Time Coding
- Phenomenology
- Receiver



MIMO Capacity Bound



Bandwidth Normalized Capacity

Channel Loss

Transmit Power (noise normalized)

$$C = \log_2(1 + |\alpha|^2 P_o) = \log_2(1 + SNR)$$

Channel Matrix

Transmit Power Matrix

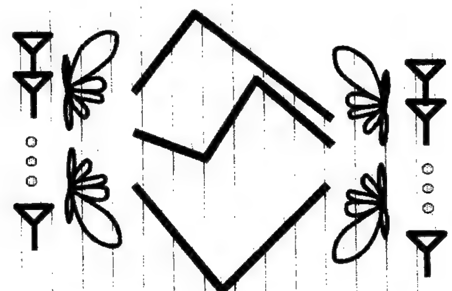
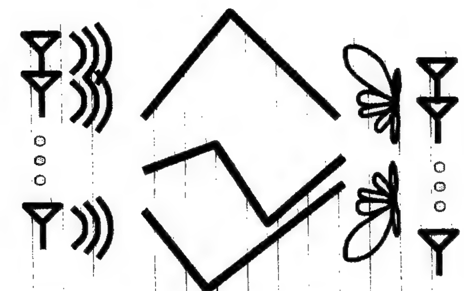
$$C = \max_{\mathrm{tr}\,\mathbf{P} = P_o} \log_2 \left| \mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{H}^\dagger \right|$$

Determinant

- **MIMO bound follows different theoretical limit**
- **Divide total energy amongst transmitters avoiding compressive regime of SISO Shannon limit**

MIMO Channel Knowledge

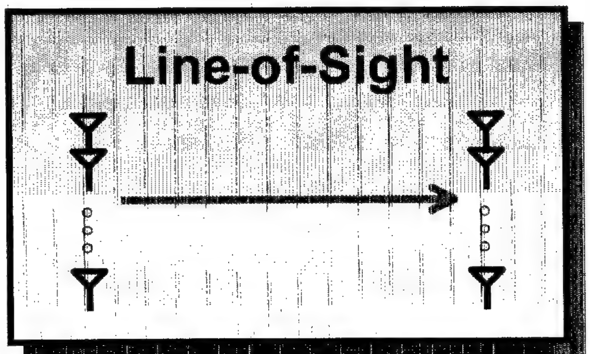
Channel knowledge affects MIMO capacity and coding

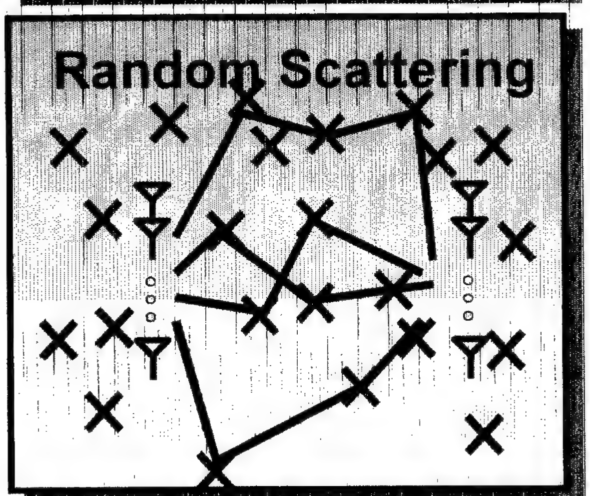
	Informed Transmitter	Uninformed Transmitter
Transmitter Channel Knowledge		
Channel Capacity (b/s/Hz)	$C_{IT} = \max_{tr\{\mathbf{P}\}=P_o} \log_2 \left\| \mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{H}^\dagger \right\|$ Determinant Transmit Power Matrix (noise-normalized)	Total Power (noise-normalized) $C_{UT} = \log_2 \left\| \mathbf{I} + \frac{P_o}{n_{Tx}} \mathbf{H}\mathbf{H}^\dagger \right\|$ Number Of Transmitters Channel Matrix

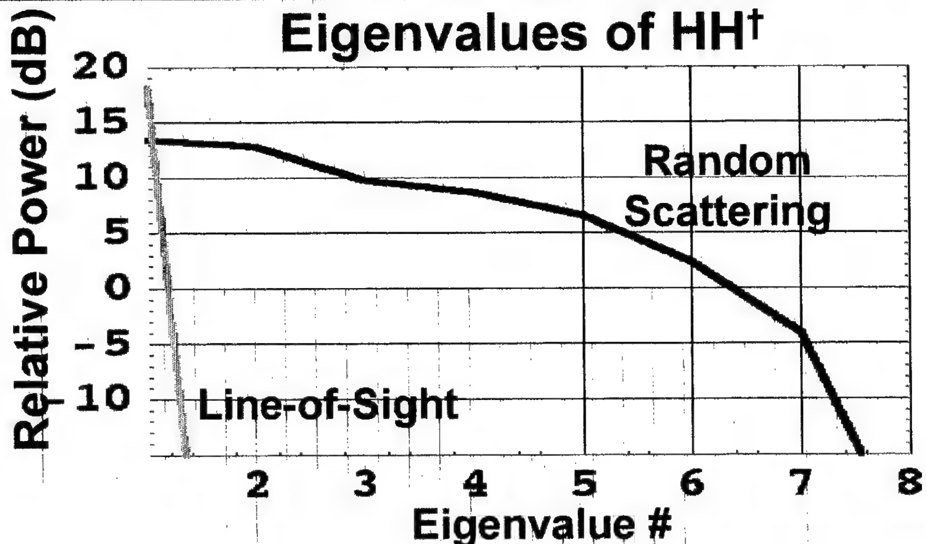
Channel Matrix

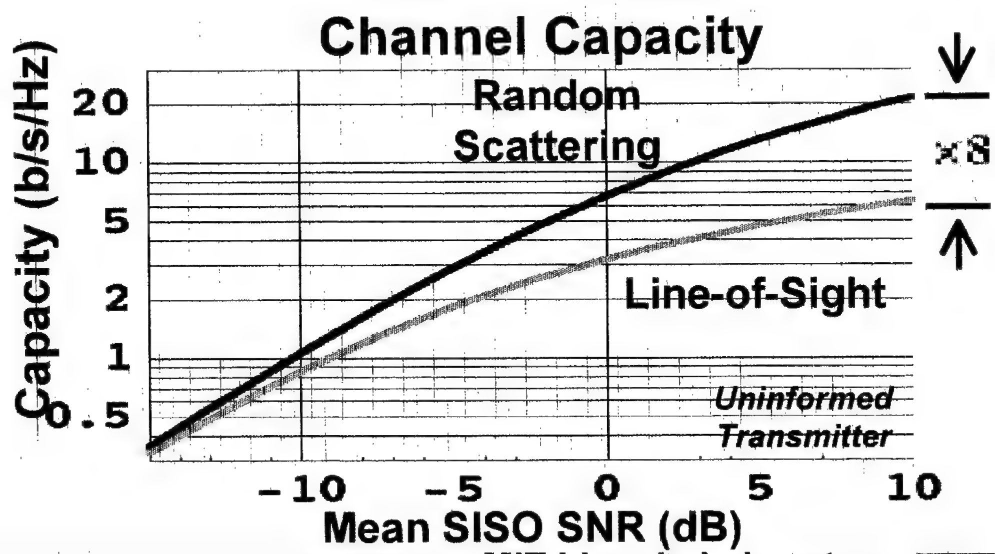
8 x 8 MIMO Example

Channel matrix, $\mathbf{H}$, contains complex attenuation between each transmit and receive antenna

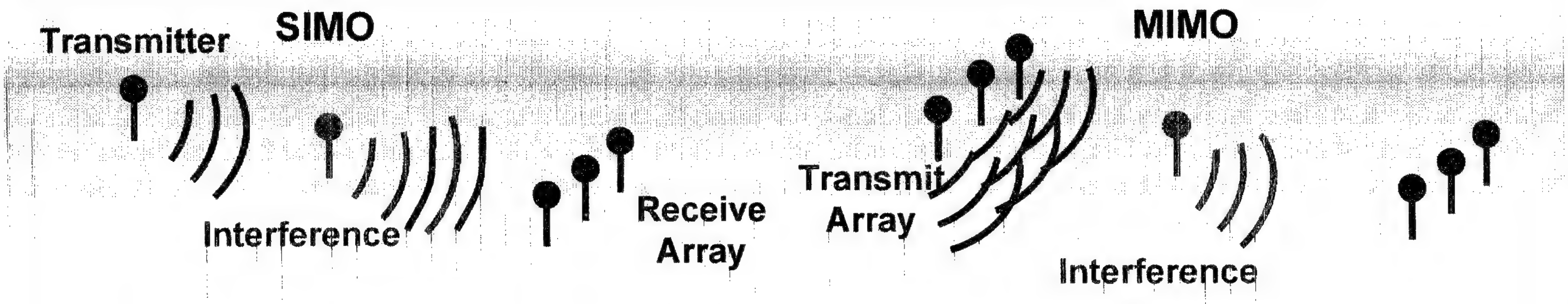






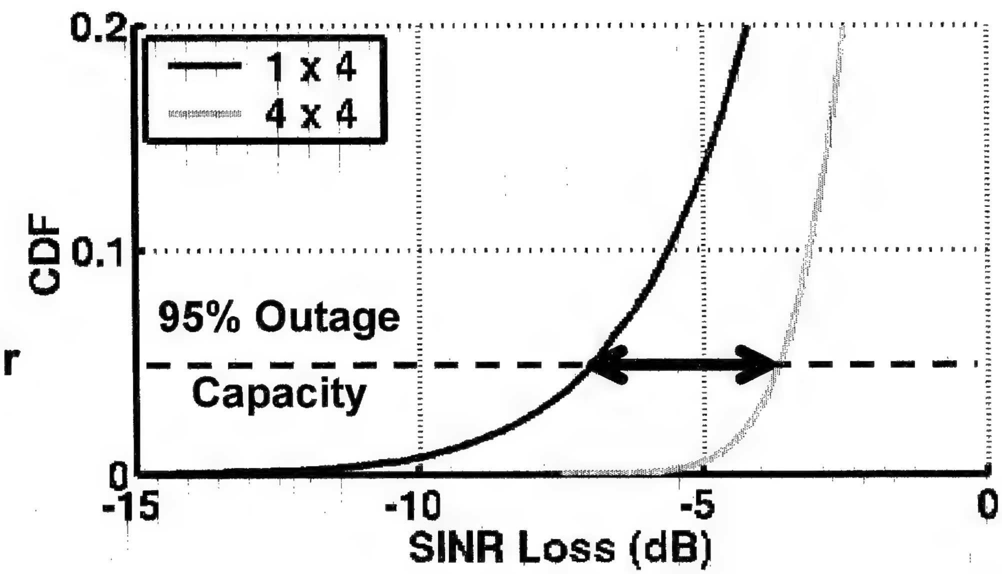


Jammer Mitigation & Avoidance
SINR Loss



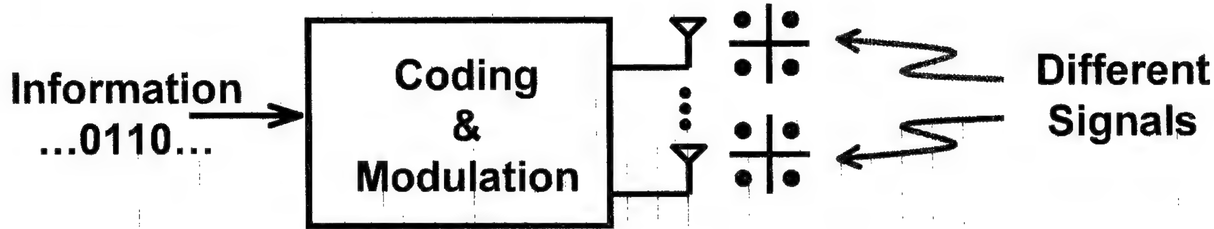
- Adaptive performance in the presence of Jammer
- MIMO has better outage capacity performance

- Assumptions
  – Single high power jammer
  – I.I.D. random Gaussian channel
  – MIMO uninformed transmitter



Space-Time Coding

- Space-time coding converts information bits to waveform distributed amongst antennas

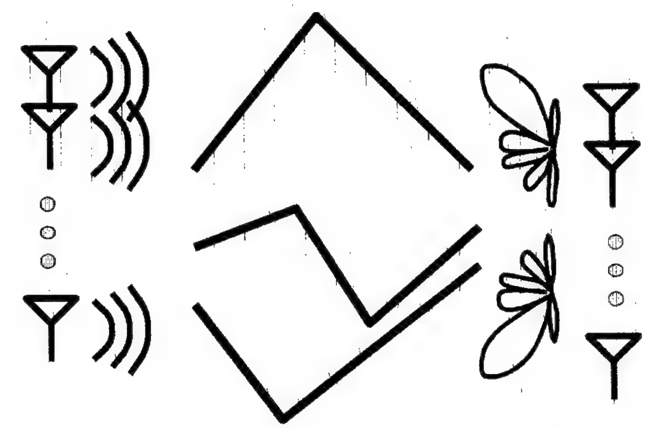


- Space-time coding analogous to conventional (SISO) coding approaches
  - Trellis
  - Low density parity check
  - Turbo

Space-Time Turbo Code Example
- Total data rate 2 b/s/Hz
- 4 transmit antennas
- 4096 bit interleavers
- QPSK constellations
- Uninformed transmitter

Topics
MIMO Communication

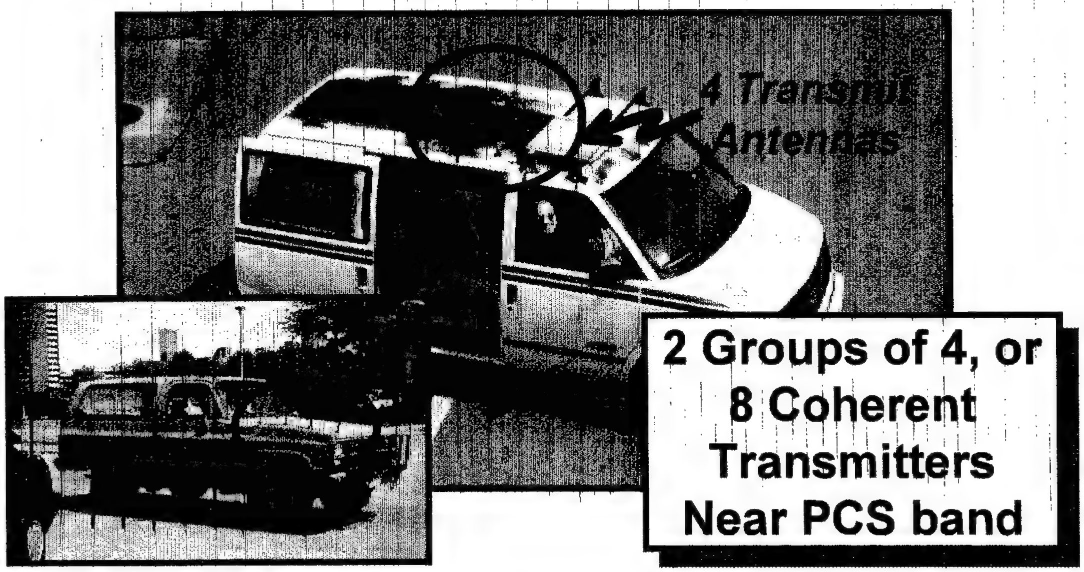
- Introduction
- MIMO Theory
- Phenomenology
  - Experimental setup
  - Phenomenology
- Receiver



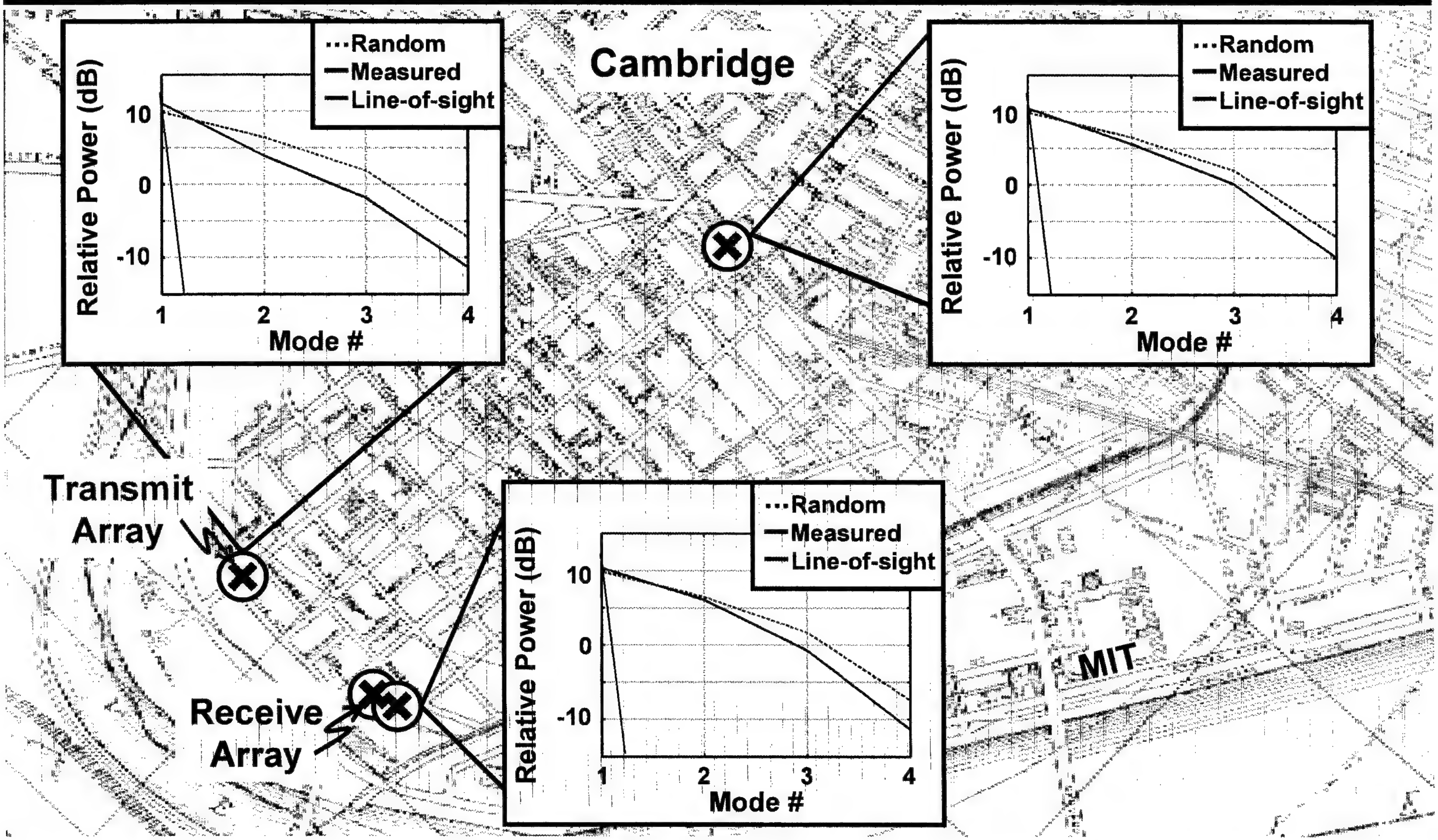
MIMO Experiment

Summer 2002

- Investigate channel phenomenology
- Study space-time coding
- Explore transmitter coherence requirements
- Demonstrate robustness to
  - Jamming
  - Cochannel interference

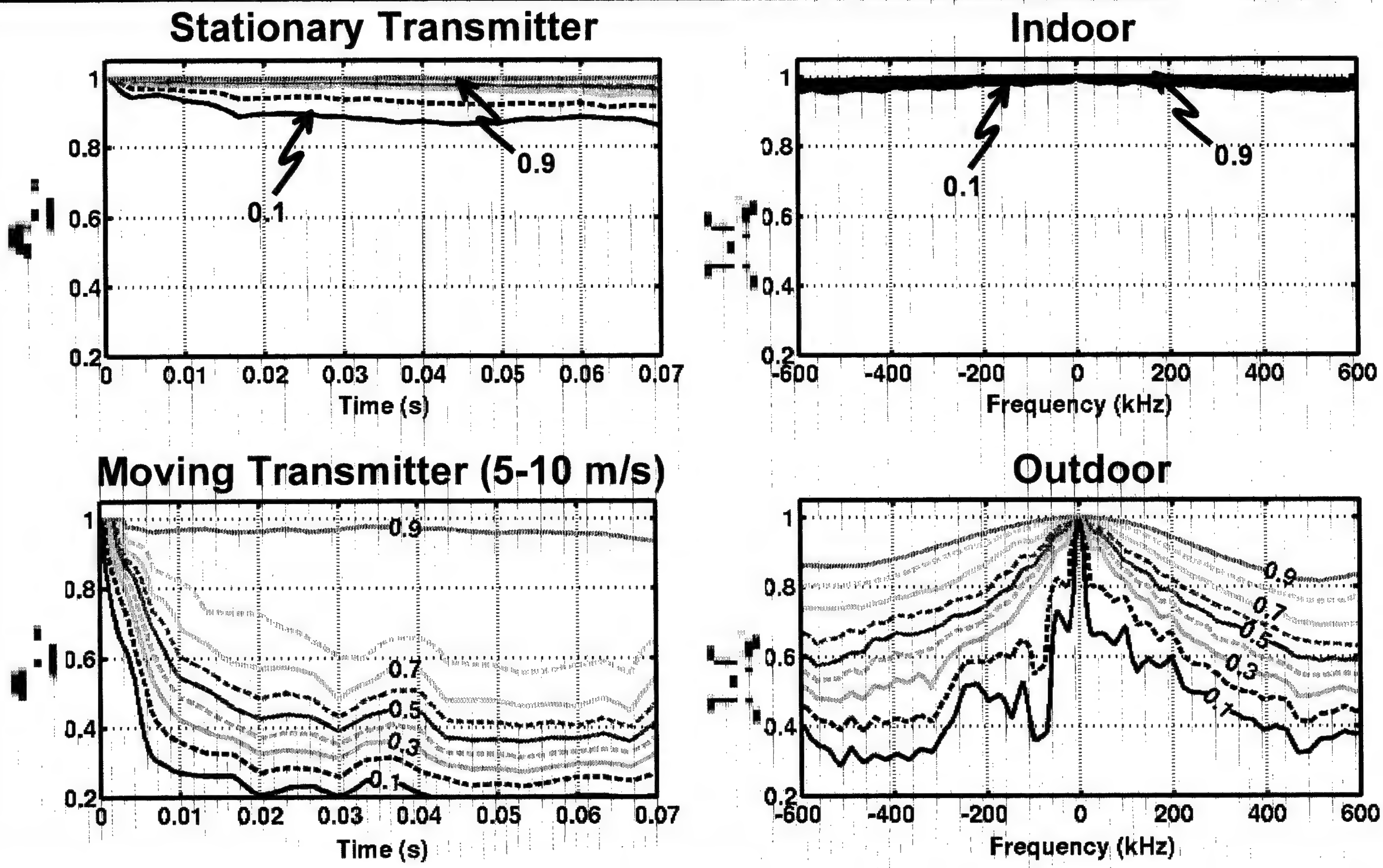


Channel Modes
Experimental Results

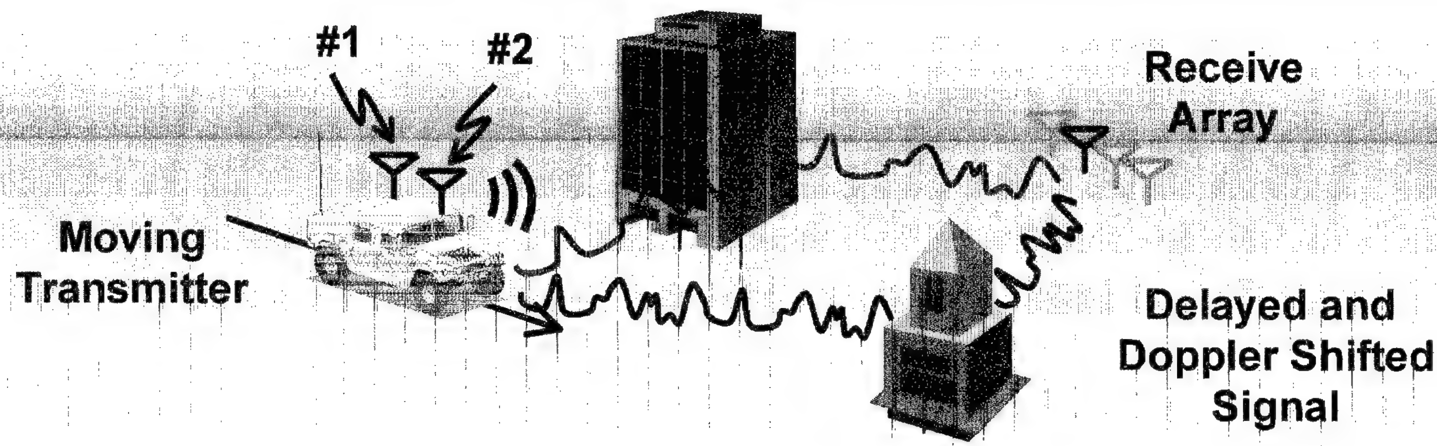


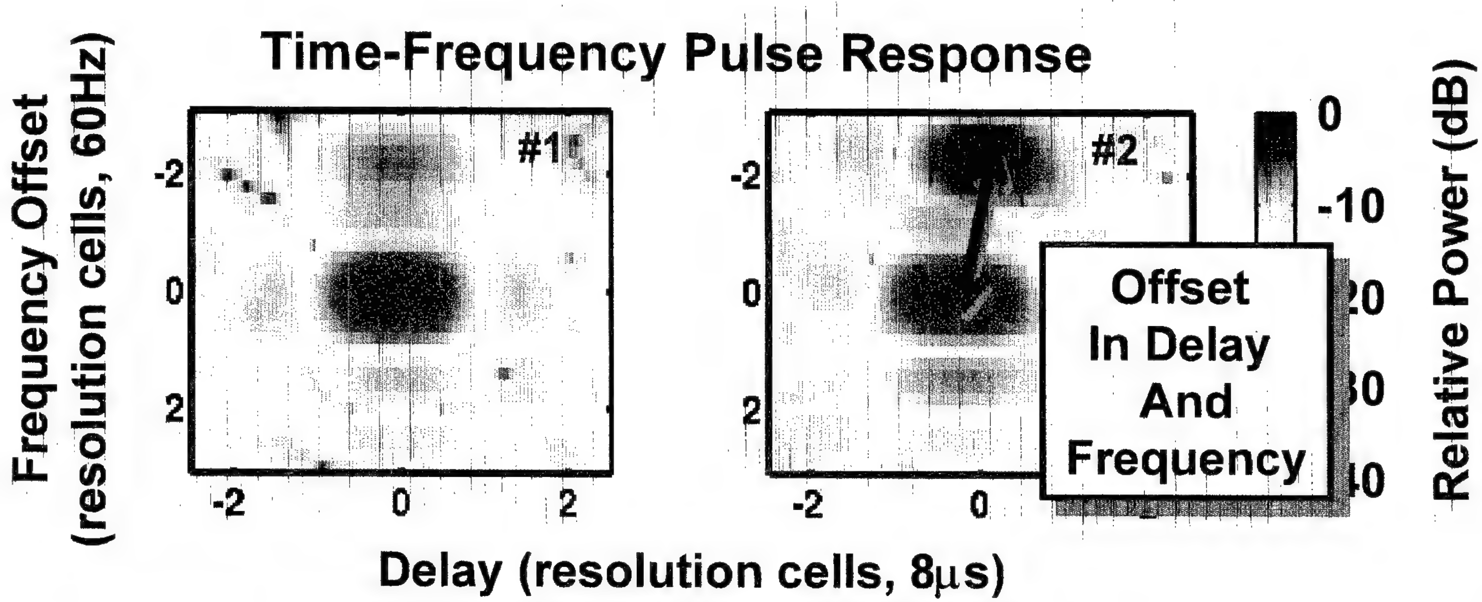
Channel Stationarity

CDF's of Power Weighted Mean $\cos^2\theta_n$



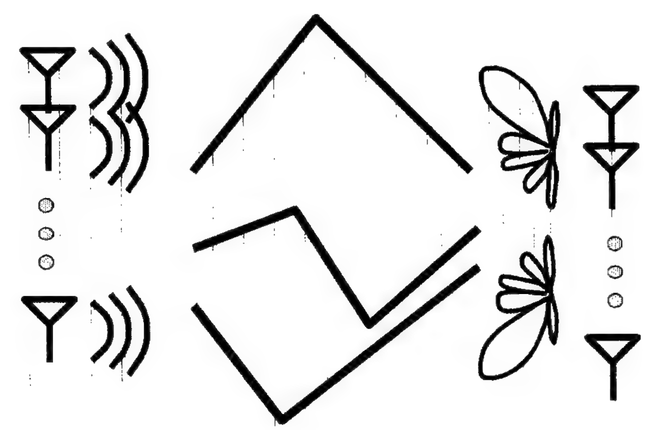
Delay-Frequency Correlations Experimental Data



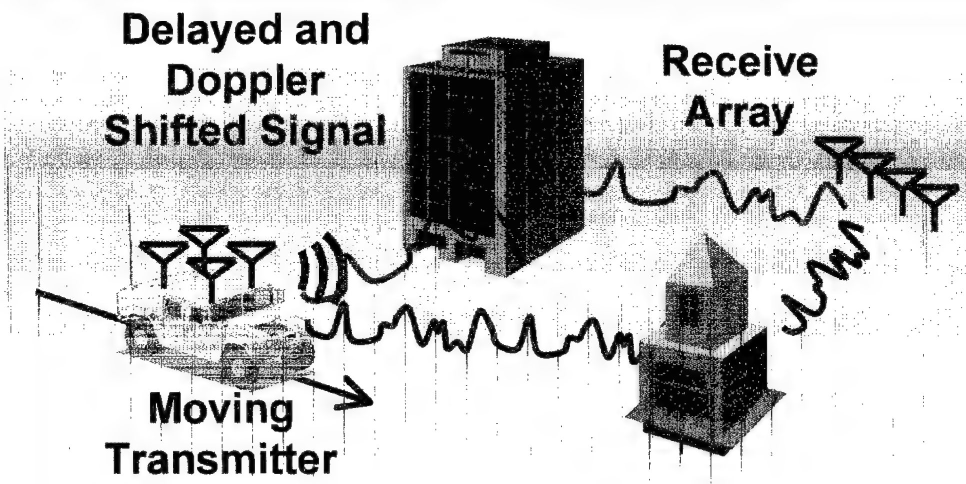


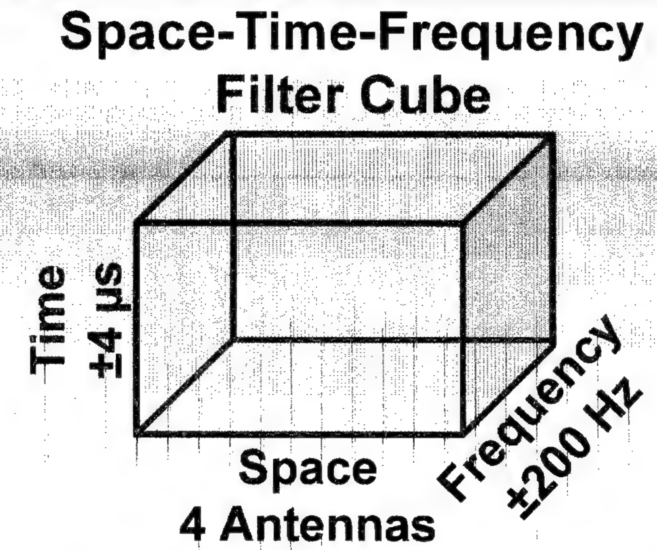
Topics
MIMO Communication

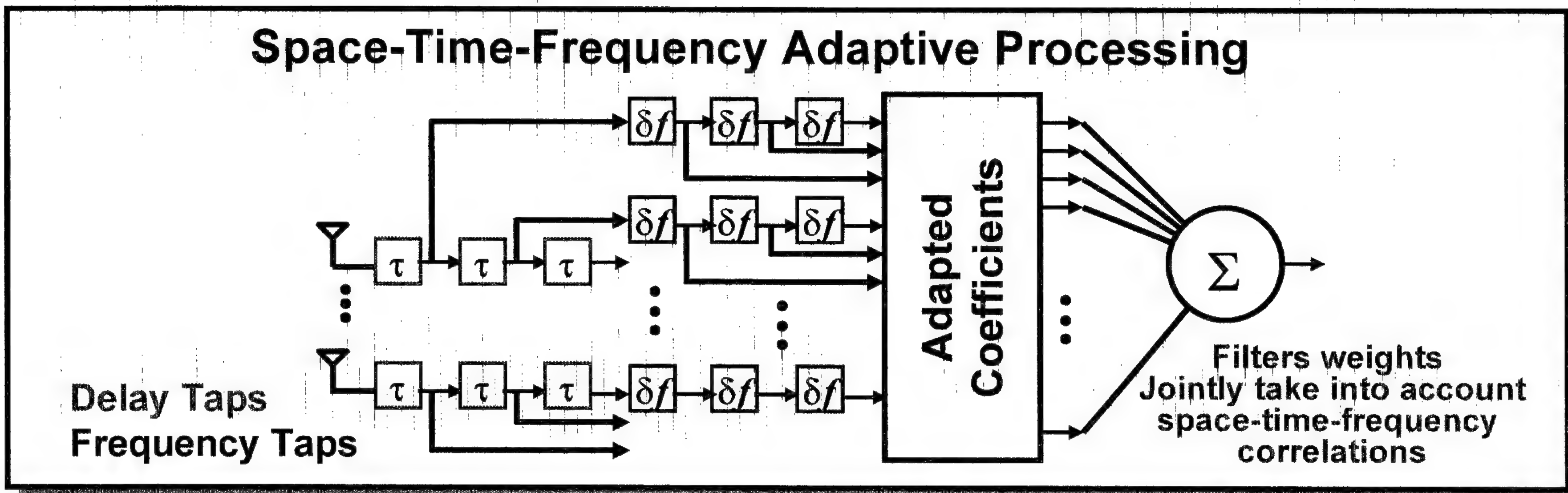
- Introduction
- MIMO Theory
- Phenomenology
- Receiver
  - Space-time-frequency adaptive processing
  - Multiuser detection
  - MCMUD
  - Experimental performance



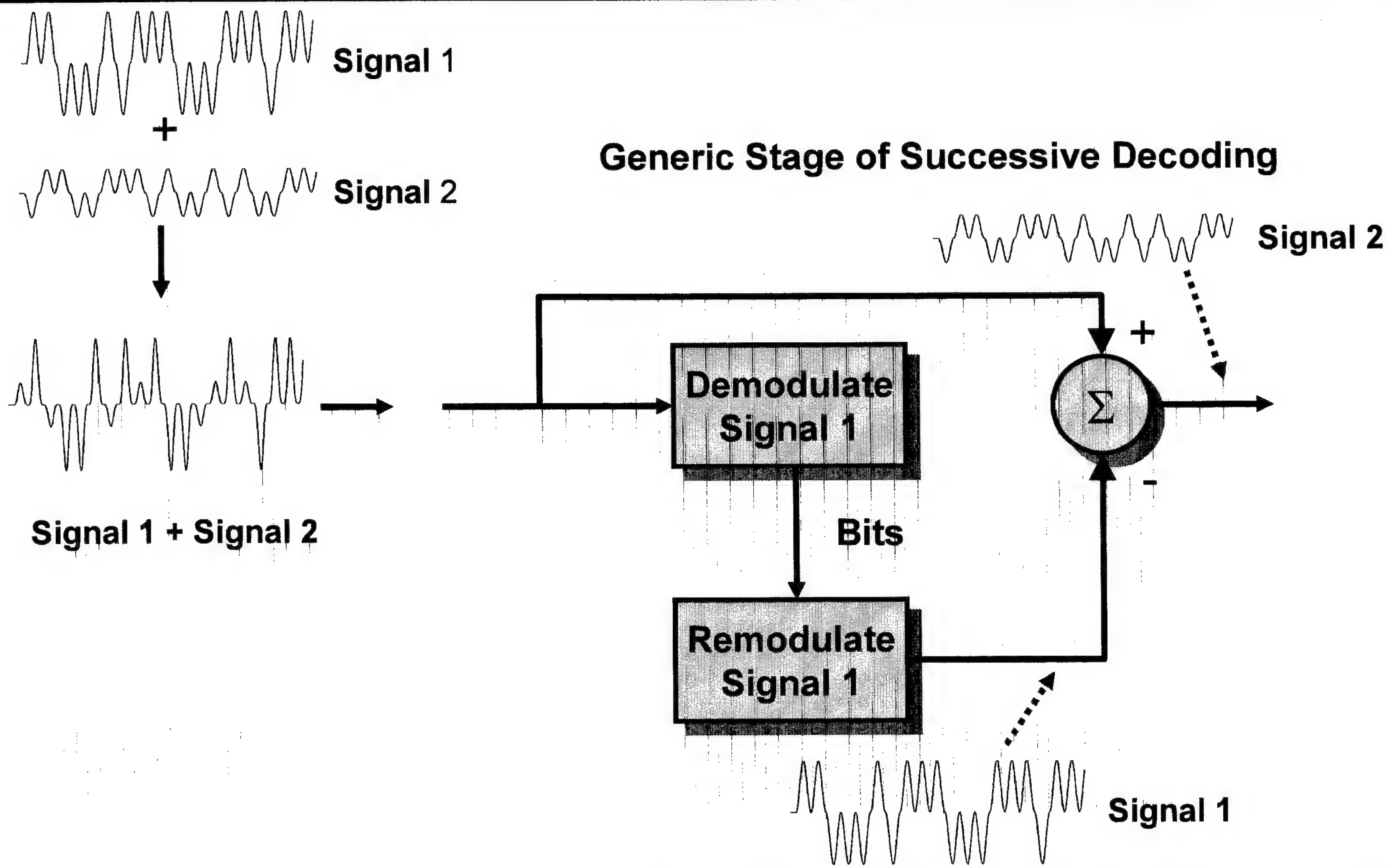
Adaptive Beamforming in Multipath







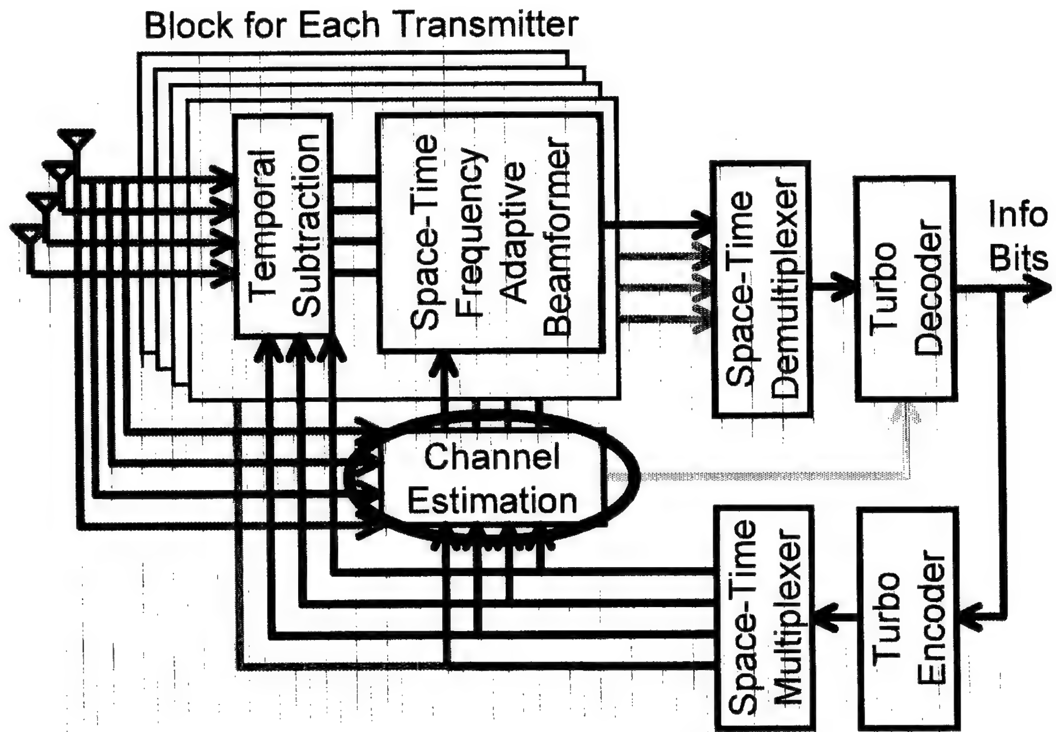
Notional Multiuser Detection



MCMUD
for Space-Time Turbo Code

- **Multichannel Multiuser Detector (MCMUD, *pat. pending*)**
- **Iterative decoder**
- **Channel estimate**
  - **Training-based**
  - **Data-directed**
- **Estimation subtraction (multiuser detection)**
- **Space-time-frequency**

  adaptive beamformers



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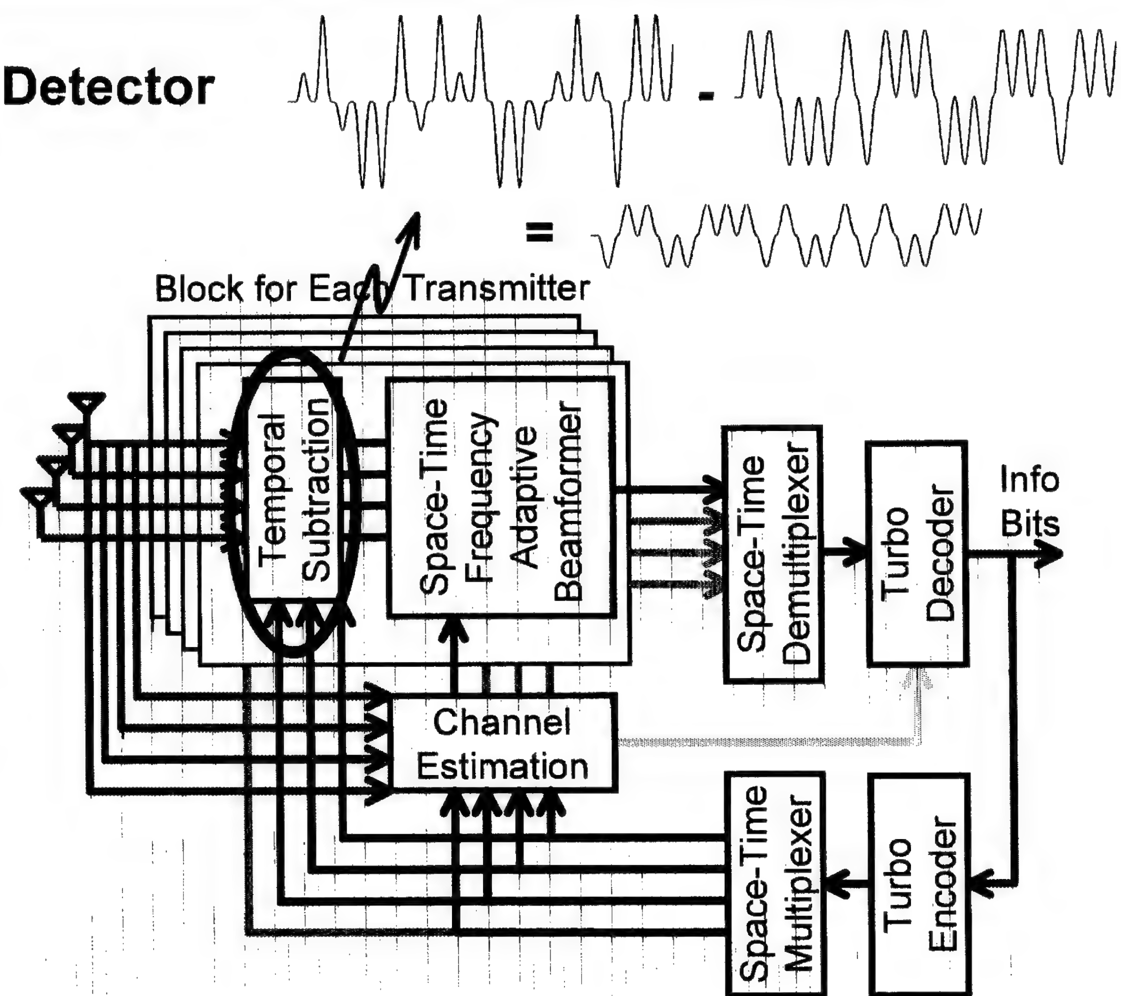
adaptive beamformers



MCMUD
for Space-Time Turbo Code

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- **Iterative decoder**
- **Channel estimate**
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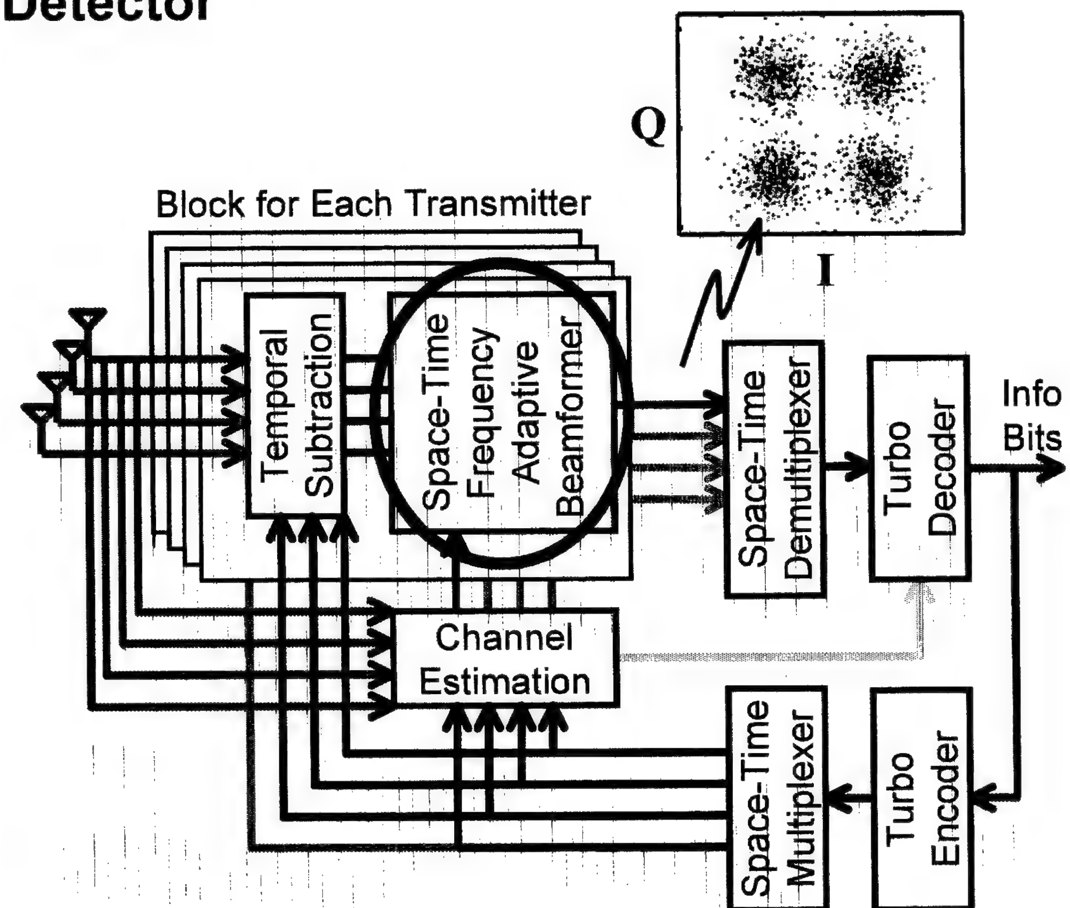
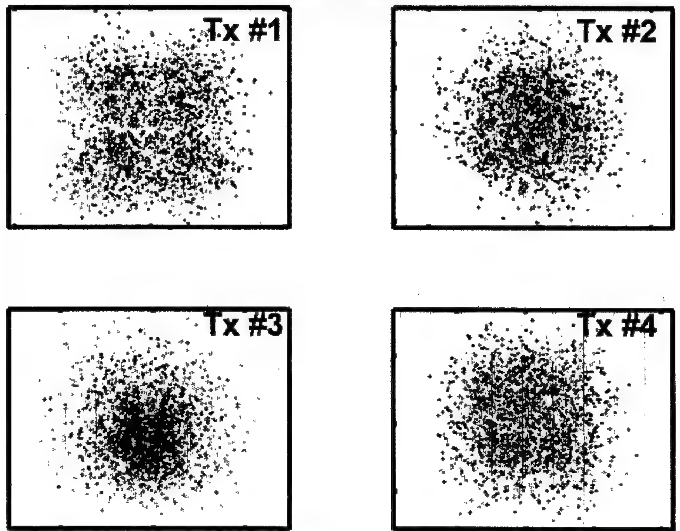
  - **Data-directed**
- **Estimation subtraction (multiuser detection)**
- **Space-time-frequency adaptive beamformers**

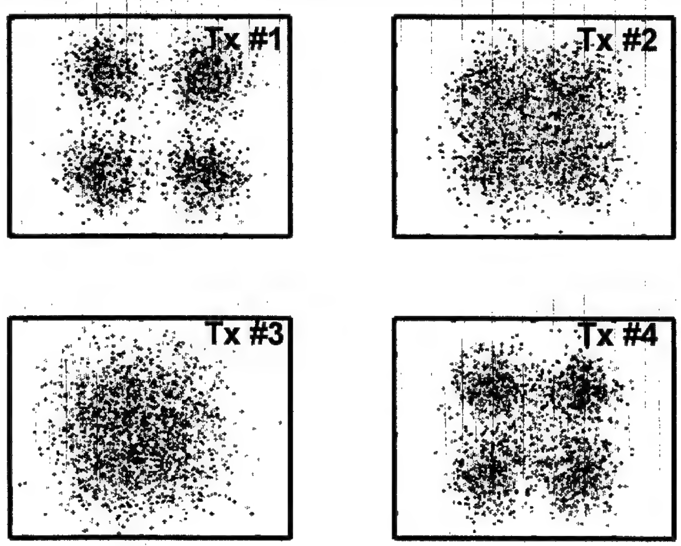


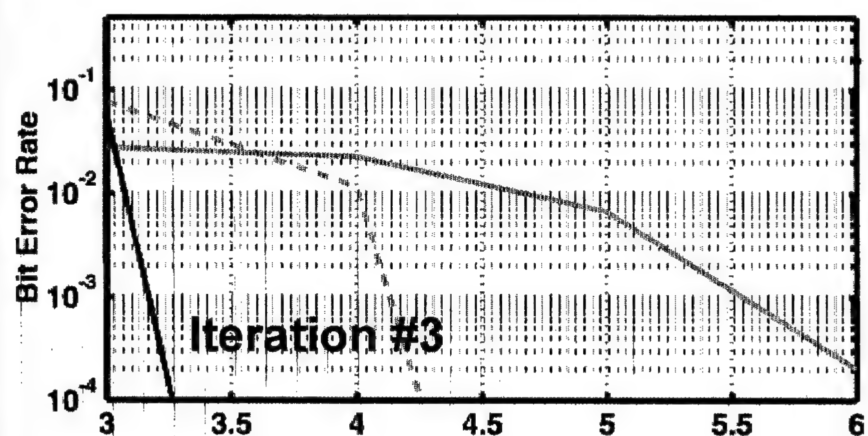
Experimental Results
Successive MCMUD Iterations

Traning-based Space-Frequency Filter

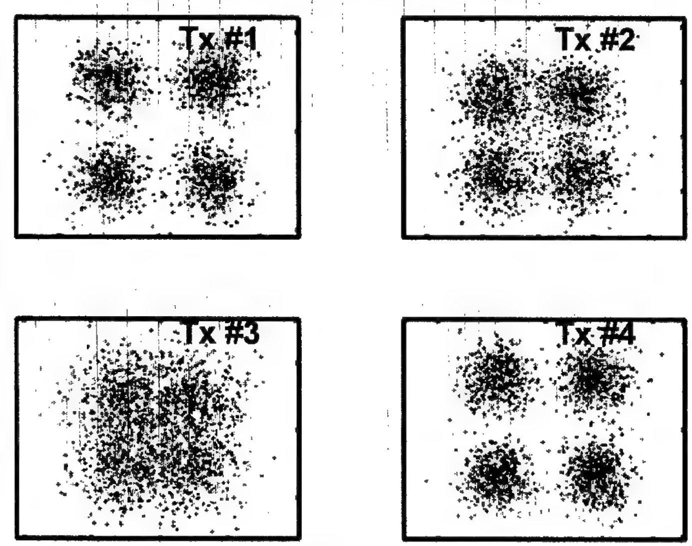


Data-Directed Space-Time-Frequency Filter



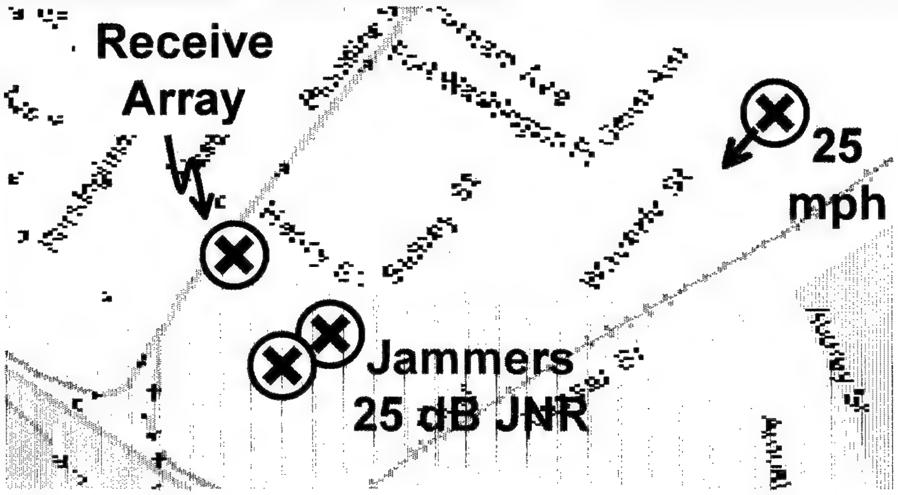


Space-Time-Frequency Filter With Multiuser Detection

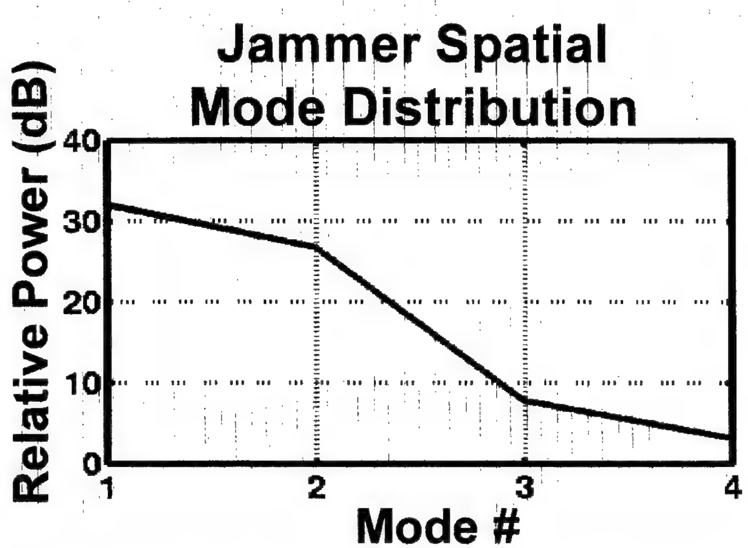


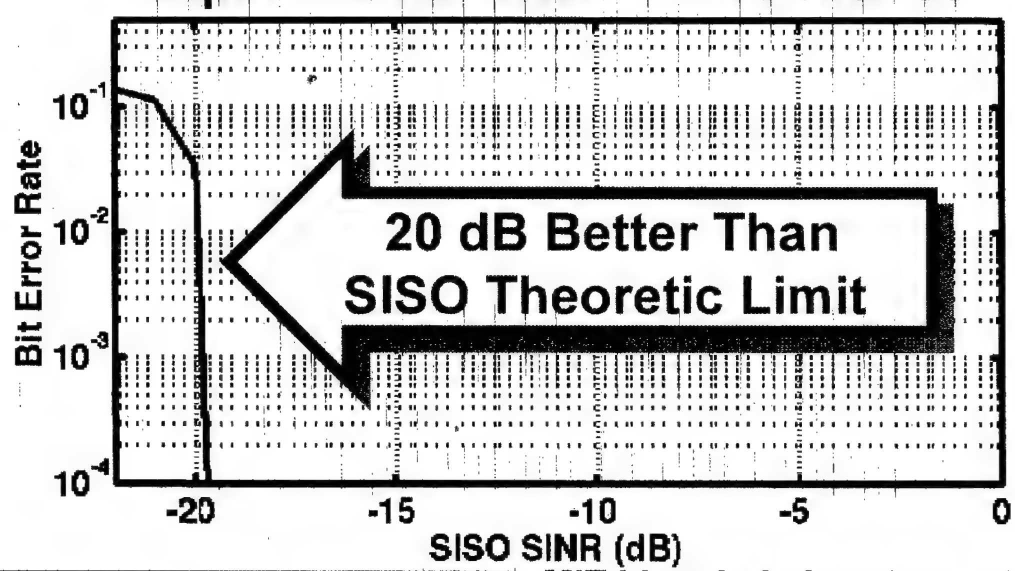
4x4 MIMO Performance

Motion, Jammers, and LO Errors



- 2 Noise Jammers (25 dB JNR)
- Moving transmitter (25 mph)
- Artificial relative local oscillator error (± 80 Hz)
- Error-free 2b/s/Hz data-link
- Near performance of jammer-free environment!





Summary

- MIMO provides robust communication links
- New receiver design concepts (MCMUD) enable communication in complicated environments
- Demonstrated dramatic performance advantages using experimental data
- MCMUD enables coherent use of ad hoc distributed networks for MIMO communication

Acknowledgements

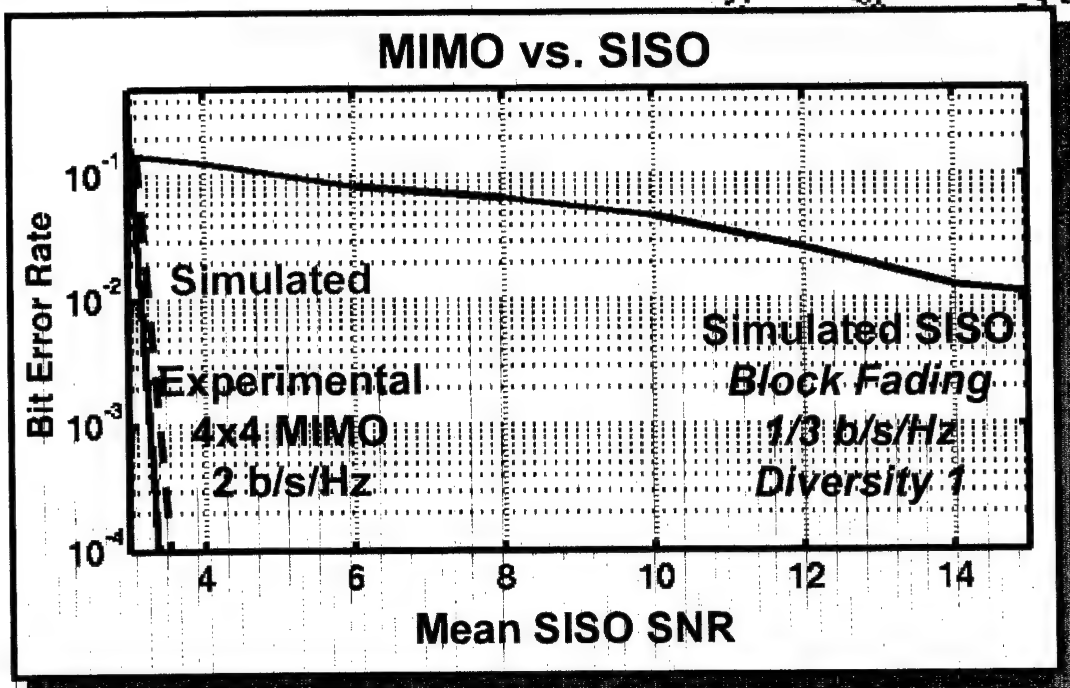
- MIT Linconln Laboratory
  New Technology Initiative Board
- Experiment team
  - Sean Tobin, Jeff Nowak, Lee Duter, John Mann, Bob Downing, Peter Priestner, Bob Devine, Tony Tavilla, Andy McKellips, Gary Hatke
- Code, algorithm and experiment design
  - Keith Forsythe, Peter Wu, Ali Yegulalp
- Analysis support
  - Amanda Chan
- Students
  - Nick Chang (U. Mich),
    Naveen Sunkavally (MIT)

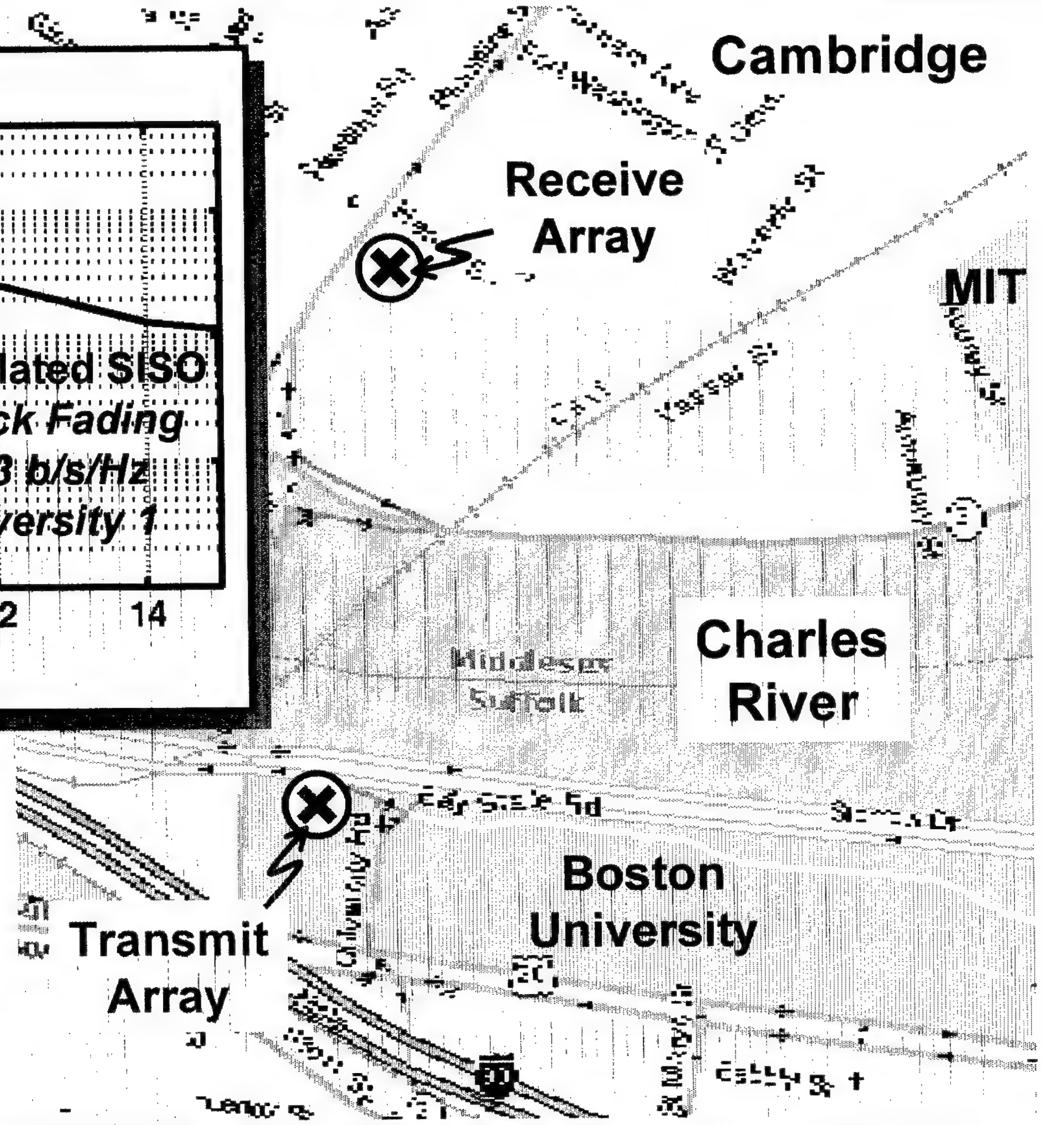
Backup Slides

Advanced Shoe-Phone Technology

MIMO Ground-to-Ground Example

Non-Line-Of-Sight





- 4 x 4 MIMO performance dramatically better than SISO
  - 6 times bit rate
  - Fading resistance
- Significant Doppler introduced by fast vehicles on Storrow Dr.

Space-Time Codes Used in Experiment

4 Transmitters

- Alamouti (2 Tx) , $\eta = 2$
- Block, $\eta = 3$
- Turbo, $\eta = 2$
- Turbo, $\eta = 4$
- CDMA, $\eta = 12/256$
- LDPC, $\eta = 1$
- LDPC, $\eta = 2$
- Trellis (Chen) , $\eta = 2$

8 Transmitters

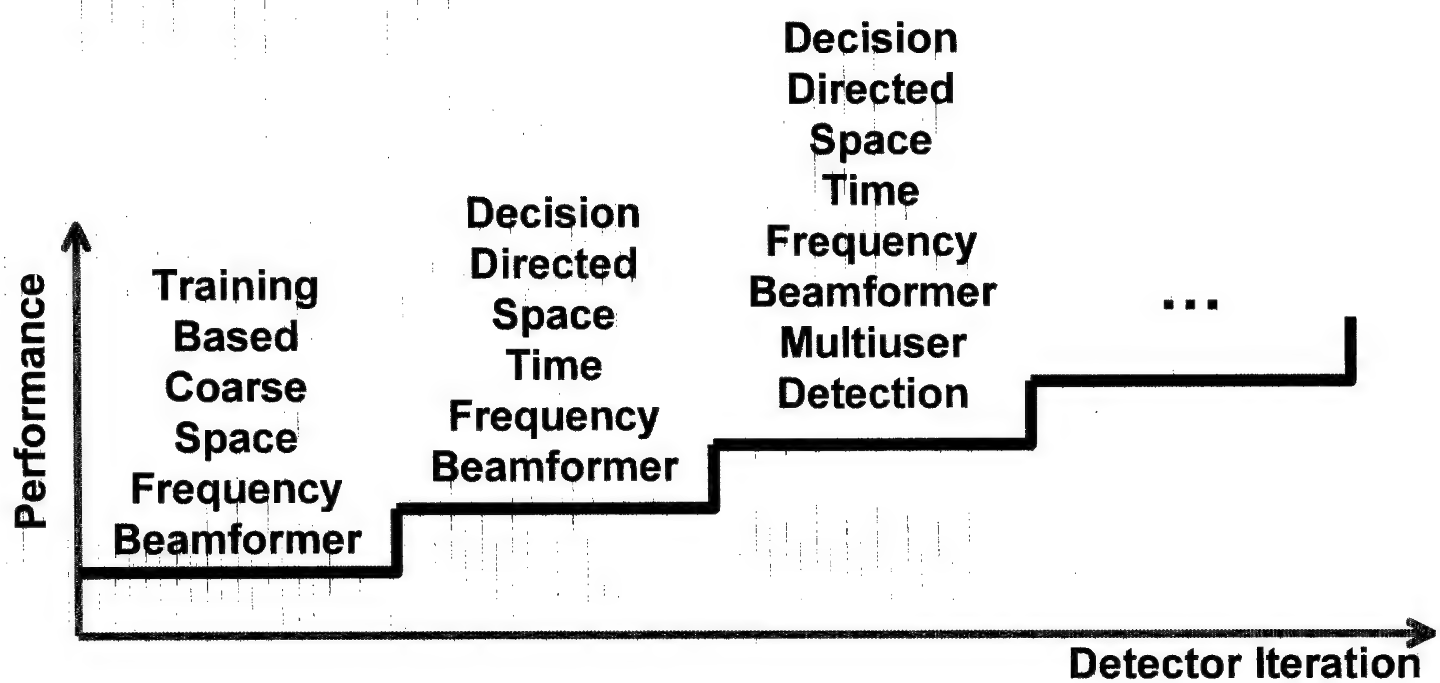
- Channel probe
- 2+2+2+2 Trellis, $\eta = 6$
- Block, $\eta = 3$
- Turbo, $\eta = 4$
- Turbo, $\eta = 8$
- CDMA, $\eta = 18/256$
- CDMA, $\eta = 20/256$
- LDPC, $\eta = 2$

Space-Time Code Source
- New Designs
- Provided by campus
- Literature

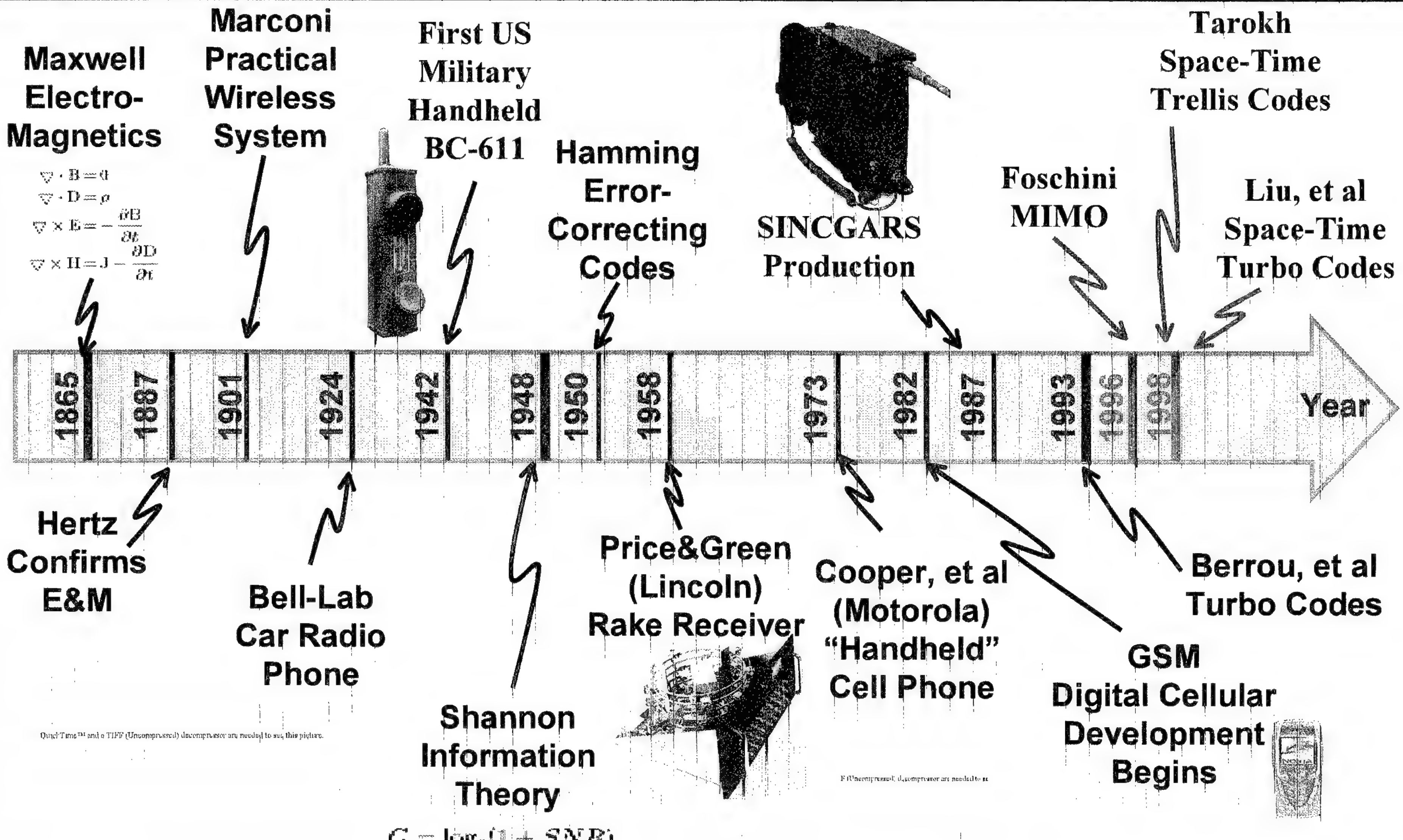
η – Spectral Efficiency (b/s/Hz)

MCMUD Detector
Progressive Complexity

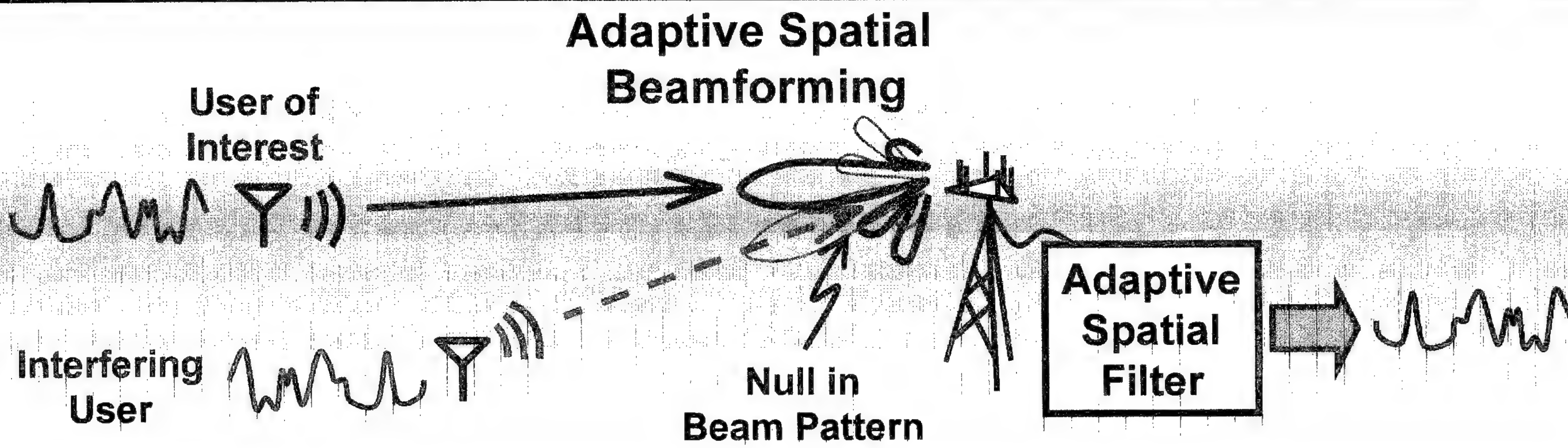
- Joint channel and data estimation
- First iteration access to limited training data or channel estimate from previous frame
- Increase detector complexity with iteration
- Increase number of turbo iterations with number of detector iterations

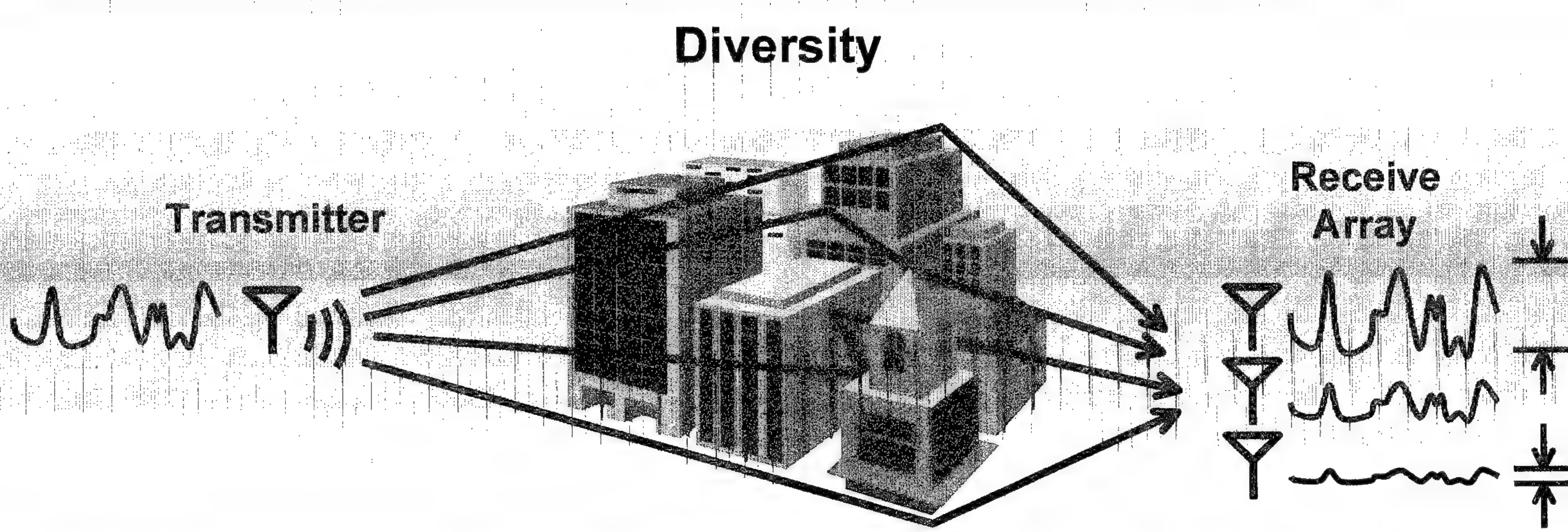


History of Wireless Communication

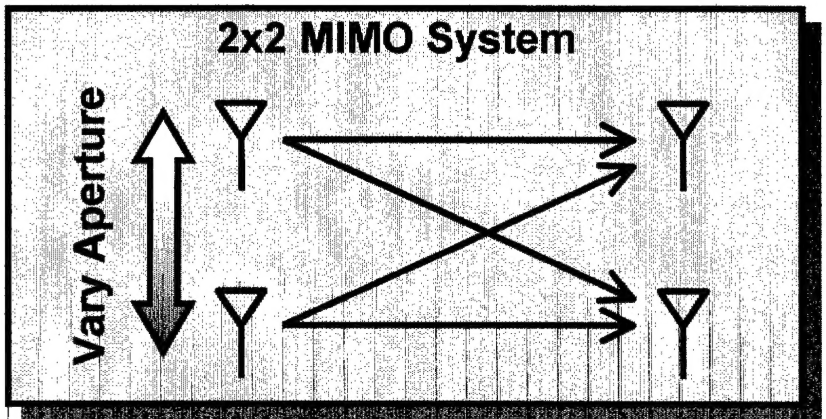


Important Antenna Array Concepts

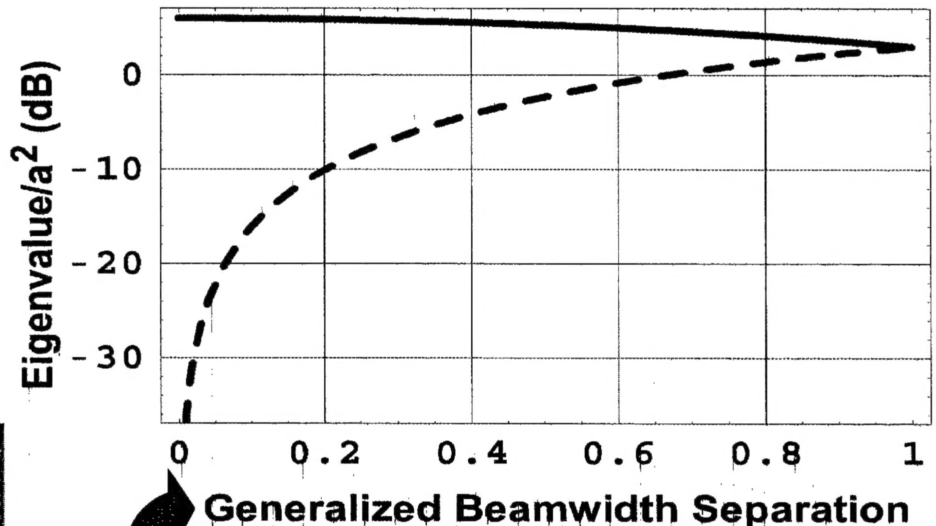




The Channel Matrix
A Toy Model



- Toy MIMO channel model
  - 2x2
  - line of sight
- Resolving individual antennas increases eigenvalue
- MIMO systems in real environments employ scatterers to increase effective aperture



$$b = \frac{2}{\pi} \arccos \frac{\left\| \vec{h}_1^{\dagger} \vec{h}_2 \right\|}{\left\| \vec{h}_1 \right\| \left\| \vec{h}_2 \right\|}$$

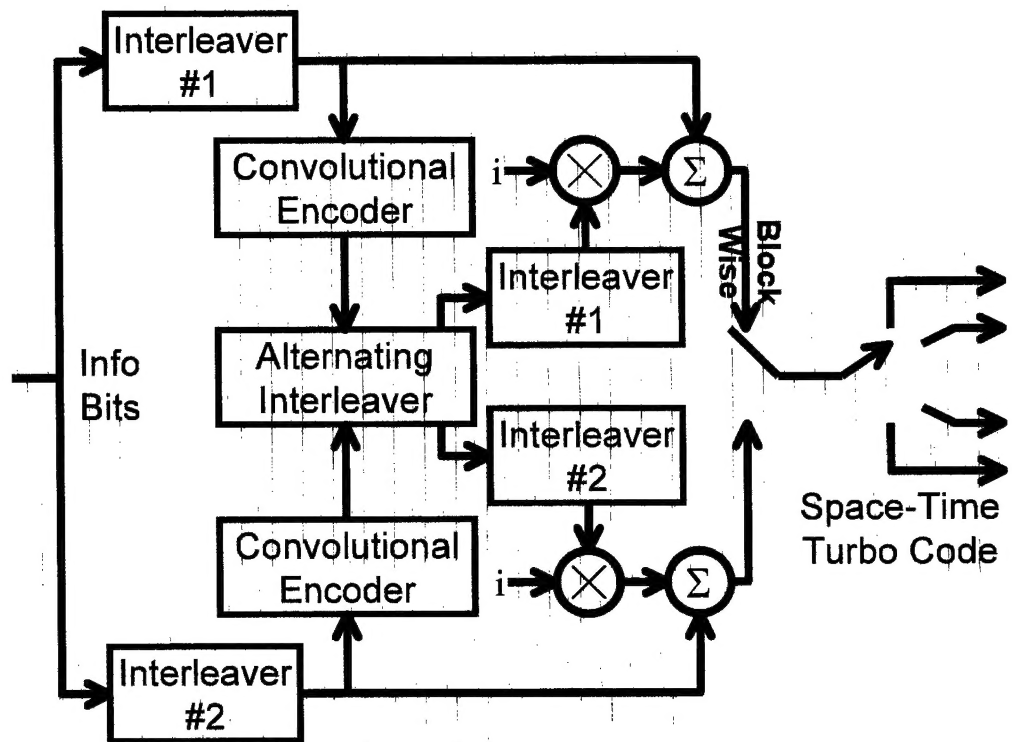
Channel Matrix, $\mathbf{H} = \begin{pmatrix} \vec{h}_1 & \vec{h}_2 \end{pmatrix}$

$$= 2\,a \begin{pmatrix} \vec{v}_1 & \vec{v}_2 \end{pmatrix}$$

Unit norm steering vector

Space-Time Turbo Code

- Block diagram for space-time turbo code
- Rate 2 b/s/Hz
- 123 kChip/s
- 4 Tx antennas
- 4096 bit interleavers
- QPSK constellation
- Optional training data



Uncooperative External Interference

Effective Loss of Complexity

- Uncooperative interference is equivalent to spatially correlated noise
- Covariance of interference plus noise

  $\mathbf{R}$

- Maximize capacity by "decorrelating" channel matrix with respect to interference

  $\tilde{\mathbf{H}} = \mathbf{R}^{-1/2}\,\mathbf{H}$

- Estimate $\tilde{\mathbf{P}}$ using new $\tilde{\mathbf{H}}$
- Modes near interference energy become less useful
- Effectively reduces the environmental complexity

Channel Capacity in Interference

Informed Transmitter **(IT)**

$$\tilde{C}_{IT} = \max_{tr\{\tilde{\mathbf{P}}\}=P_o} \log_2\left|\mathbf{I} + \tilde{\mathbf{H}}\tilde{\mathbf{P}}\tilde{\mathbf{H}}^{\dagger}\right|$$

Interference Whitened Channel Matrix

Noise-Normalized Transmit Covariance Matrix

Uninformed Transmitter **(UT)**

$$\tilde{C}_{UT} = \log_2\left|\mathbf{I} + \frac{P_o}{n_{Tx}}\tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\dagger}\right|$$

The Channel Matrix

- Channel matrix, $\mathbf{H}$, contains complex attenuation between each transmit and receive antenna
- Large channel eigenvalues of $HH^{\dagger}$ are useful